European Journal of Operational Research 248 (2016) 123–135

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Production, Manufacturing and Logistics

Minimising total tardiness for a single machine scheduling problem with family setups and resource constraints

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ARTICLE INFO

Article history:
Received 3 March 2015
Accepted 1 July 2015
Available online 8 July 2015

Keywords:
Single-machine scheduling
Family scheduling
Tardiness minimisation
Resource constraints

ABSTRACT

This paper considers a single machine scheduling problem in which each job to be scheduled belongs to a family and setups are required between jobs belonging to different families. Each job requires a certain amount of resource that is supplied through upstream processes. Therefore, schedules must be generated in such a way that the total resource demand does not exceed the resource supply up to any point in time. The goal is to find a schedule minimising total tardiness with respect to the given due dates of the jobs. A mathematical formulation and a heuristic solution approach for two variants of the problem are presented. Computational experiments show that the proposed heuristic outperforms a state-of-the-art commercial mixed integer programming solver both in terms of solution quality and computation time.

1. Introduction

In this paper we study the problem of scheduling jobs on a single machine with the goal of minimising total tardiness. Each job has a given processing time, a due date, and belongs to a given family. The machine can only process one job at a time and each job must be processed without preemption. A setup task has to be conducted between jobs belonging to different families and during this setup the machine cannot process any job.

The problem studied in this paper, each job requires a certain amount of a common resource that is supplied through upstream processes. At any time, the cumulative consumption must not exceed the cumulative supply. Therefore, jobs may have to wait due to an insufficient availability of the resource.

Fig. 1 illustrates the implication of the resource constraints. The figure shows the cumulative amount of resource supplied and the cumulative amount of resource required over time. The cumulative amount of resource supplied is shown as a linear curve with a constant supply rate. The cumulative resource demand over time is shown as a piece-wise linear curve that increases whenever a job is processed. The dotted vertical lines illustrate completion times of individual jobs. Horizontal segments of the demand curve illustrate times during which the machine has not yet started processing the next job, e.g. because a setup is conducted. As the cumulative amount of resource required must not exceed the cumulative amount of resource supplied at any time and because each job must be processed without preemption, the machine may also have to be idle before starting to process a job due to limited resource availability.

Our work is motivated by a practical problem arising in the continuous casting stage of steel production. A continuous caster is fed with ladles of liquid steel. Each ladle contains a certain steel grade and has orders allocated to it that determine a due date. Whenever two ladles of similar steel grade (within one setup family) are processed consecutively, no setup process is necessary. However, a setup is required whenever changing to a steel grade from another setup family. The liquid steel is produced from hot iron supplied by the blast furnace with a constant rate. The sequence of ladles, including setups between ladles of different setup families, is not allowed to consume more hot metal then supplied by the blast furnace (see e.g. Box & Herbe, 1988).

Similar situations occur in multi-stage production processes, where upstream work systems supply the common resource that is consumed by the jobs produced on the machine. Examples can be found in assembly processes where parts and components provided by an upstream stage are used to assemble different products (e.g. Drótos & Kis, 2013, cutting pieces from a steel slab).

The remainder of this paper is organised as follows. Section 2 gives an overview of related work. Section 3 contains a detailed description of the problem and presents MIP formulations for two variants of the problem. In Section 4 we present an iterated local search approach for solving the problem. Section 5 presents computational experiments before final remarks are given in Section 6.

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http://dx.doi.org/10.1016/j.ejor.2015.07.001
0377-2217/

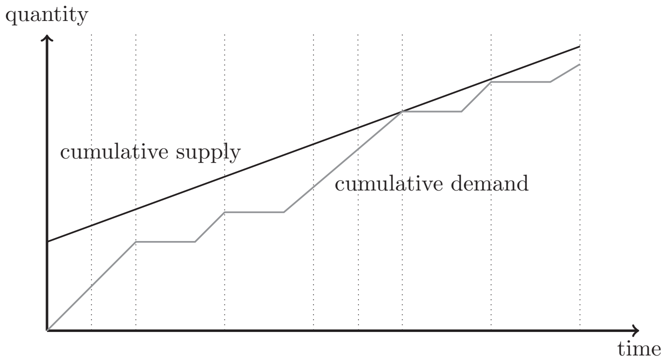

Fig. 1. Depiction of the resource constraint in the context of scheduling with family setup times.

2. Related work

There are three main streams of literature that are of interest for the problem studied in this paper. First, scheduling with the target of minimising total tardiness. Second, single machine scheduling with setup considerations. Third, scheduling with resource constraints.

Comprehensive surveys for the minimum tardiness scheduling problem are presented by Koulamas (2010) and Sen, Sulek, and Dileepan (2003). Even without setup considerations, the single machine total tardiness problem is proven to be NP-hard (Du & Leung, 1990). Most methods developed for single machine problems that minimise total tardiness use properties developed by Emmons (1969) and Lawler (1977). Emmons (1969) describes conditions that need to be fulfilled in an optimal schedule, and Lawler (1977) introduced a decomposition approach that separates a problem into two mutually exclusive sub problems using the longest job to separate. For the problem of scheduling independent jobs on identical parallel machines, Shim and Kim (2007) present a branch and bound algorithm to minimise total tardiness. Schaller (2009) presents improved lower bounds that can be used in this branch-and-bound algorithm to reduce the computational effort required. Recently, Lee and Kim (2015) present a branch-and-bound algorithm for the problem of minimising the total tardiness of jobs in which for both of the two identical machines periodic maintenance activities are required during which the machine cannot process any job. Furthermore, Mensendiek, Gupta, and Herrmann (2015) developed properties for optimal sequences with the total tardiness objective on parallel machines with fixed delivery dates and present heuristics for solving the problem.

The literature on scheduling with setup considerations is summarised e.g. in surveys of Allahverdi, Ng, Cheng, and Kovalyov (2008) and Potts and Kovalyov (2000). For the problem of minimising total tardiness on a single machine with sequence-dependent setup times, Gupta and Smith (2006) presented a GRASP multi-start heuristic as well as a space-based local search procedure, Liao and Juan (2007) developed a method based on ant colony optimization, Lin and Ying (2008) a hybrid of simulated annealing and tabu search, Ying, Lin, and Huang (2009) an iterated greedy heuristic based on local search, and Sioud, Gravel, and Gagné (2012) a hybrid genetic algorithm. An exact branch-and-bound algorithm for this problem class is presented by Bigras, Gamache, and Savard (2008). For the variant of the problem where the goal is to minimise the weighted tardiness of all jobs, Tanaka and Araki (2013) recently developed an exact procedure based successive sublimation dynamic programming and Subramanian, Battarra, and Potts (2014) recently presented an iterated local search heuristic.

In family scheduling problems, all jobs are assigned to a certain family and a set of jobs of the same family that is produced consecutively without a setup is called a *batch*. While the allocation of jobs to families is given as a parameter, the allocation of jobs to batches for a certain setup family is part of the decision process. Under the *group technology assumption (GTA)* (see e.g. Potts & Van Wassenhove, 1992) all jobs of the same setup family must be produced within exactly one batch, while several batches of the same family can be scheduled in the general case that is considered in this paper.

Gupta and Chantaravarapan (2008) and Schaller (2007) study a family scheduling problem in which the goal is to minimise total tardiness. Gupta and Chantaravarapan (2008) studied the problem under consideration of the GTA. They present a MIP formulation to solve small problem instances as well as a heuristic algorithm for larger instances. In their heuristic the authors separate the sequencing of jobs within a batch and the sequence of batches. Inside each batch they used a combination of neighbourhood operators previously developed by Holsenback and Russell (1992) and Panwalkar, Smith, and Koulamas (1993).

Schaller (2007) studied the family scheduling problem with and without the GTA. Based on the properties described by Emmons (1969), two optimal branch and bound procedures for both cases are developed. Furthermore, a heuristic based on five local search moves is proposed. These moves include the combining of two batches of the same setup family, moving jobs between batches of the same setup family, breaking a batch into two parts, and interchanging pairs of jobs. Furthermore, Schaller and Gupta (2008) study the minimisation of both earliness and tardiness for a single machine scheduling problem with family setups and propose exact and heuristic methods with and without the GTA. More recently, Schaller (2014) presents several heuristic approaches for scheduling identical parallel machines with family setups for the problem of minimising total tardiness.

Grigoriev, Holthuijsen, and Van De Klundert (2005) provide a survey on scheduling problems with raw material constraints. They distinguish between three types of raw material usages: (a) each job has its own raw material, (b) a common resource is required by all jobs, and (c) multiple common raw materials are required for each job. For all three cases they considered the objective of minimising maximum lateness and minimising makespan. Briskorn, Choi, Lee, Leung, and Pinedo (2010) study a single machine scheduling problem where jobs cannot be processed if the required resource is not available. Among the objectives considered are the objectives of minimising maximum lateness and minimising the number of tardy jobs. Györgyi and Kis (2014) study variations of the problem of minimising makespan with resource constraints using propositions from the knapsack and vertex cover problems to develop a polynomial-time approximation scheme. Briskorn, Jaehn, and Pesch (2013) study the single machine problem with inventory constraints to minimise the weighted sum of completion times. The authors derived properties for an optimal solution and developed a branch and bound as well as a dynamic programming approach to solve the problem. They conclude that even for small problem instances with 20 jobs, exact approaches are not efficient enough and heuristic approaches are required. None of these works considers the objective of minimising total tardiness.

While previous work on family scheduling problems does not include resource constraints, papers published on scheduling problems with resource constraints do not consider family setups. To the best of our knowledge, the single machine scheduling problem with family setups and resource constraints has not been studied.

3. Problem description

The machine scheduling problem studied in this paper can be described as follows. Let J denote a set of jobs to be processed by a single machine. Each job is characterised by a due date d_j, a processing time p_j, and the quantity q_j of a resource required by the machine to process the job. It is assumed that the resource is consumed at a constant